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Measurements of AC Losses in HTSC Wires Exposed to an Alternating Field using Calorimetric Methods

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***Abstract*—Calorimetric methods for AC loss measurement for short superconducting wires have been investigated. The design, operation and results obtained from an experimental calorimeter will be described. With these methods the total loss of a short superconducting sample exposed to a 50 Hz alternating field, both perpendicular and axial, have been measured with an accuracy of microwatts per centimeter. The sample is a 6 centimeter long (Bi,Pb)SrCaCuO-2223 silver-sheathed multifilamentary wire prepared by powder-in-tube techniques. The hysteresis part of the loss may be obtained by taking the eddy current component of the silver sheath from the total loss and by neglecting the coupling loss in the silver matrices. It is shown that the hysteresis losses are dominant in this frequency and its values correspond to the theoretical approximation.**

I. INTRODUCTION

The most promising products of high temperature superconductor (HTSC) technology are silver sheathed BSCCO-2223 tapes. Due to their relatively high critical current density at high temperature and the ability to make flexible and long wires, these products have been considered for power engineering applications. One burden in utilizing these products is the losses when operating in alternating current and/or field. Different studies on these losses have been carried out with various methods and approaches. While methods such as magnetization as well as transport methods have been used for measuring and analyzing AC losses [1-7], calorimetric methods provide other advantages of studying these losses [8-11].

The losses of tapes carrying AC currents have been understood using critical state models as explained by Bean [12] while their estimations have been perfectly explained using Norris equations [13]. Another interesting area is to measure and analyze the loss behavior of HTSC tape when exposed to an AC magnetic field. Ishii et al. have studied these losses using magnetization techniques [1]. Other techniques are also used [10] with their advantages and limitations.

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This work will describe methods of measuring losses of a short HTSC sample subjected to an alternating field using calorimetric methods. These methods have been successfully used in previous work to measure the losses of a short HTSC wire carrying AC current [8]. In recent work the losses of a 37-multifilamentary sample exposed to a 50 Hz field are measured and analyzed. The behavior of the losses of the sample seems to be corresponding to the theoretical approximations.

II. EXPERIMENTAL METHODS

The test rig used for these measurements consists of a calorimeter and associated data acquisition and other apparatus. The calorimeter uses two resistance temperature devices to measure the slight temperature increases of the sample. Passing an AC current through a solenoid coil generates an alternating field. The field is assumed to be homogeneously distributed within the sample length. Fig. 1 shows the instrumentation rig for the measurements. A thermal insulator as depicted in Fig. 2 surrounds the sensors, a heater and an HTSC sample.

The temperature sensors are then attached to a digital multimeter to measure their resistances and this reading is next transferred to a personal computer and converted to their temperature value. A DC current source, together with the heater, is needed for the system calibration. The critical current of the sample is identified using a conventional four-probe technique before and after the AC loss measurement to confirm that their values have not changed.

The total loss, P_t, of the superconducting sample is calculated using:

$$P_t = \frac{\Delta T}{R_{th}}, \tag{1}$$

where ΔT is the temperature increase in K and R_{th} is the thermal resistance of the calorimeter in K/W.

A calibration curve is firstly constructed to determine the thermal resistance of the calorimeter by passing a DC current I to the heater within a certain time duration τ_m chosen to be long enough for the temperature to become steady. Then a

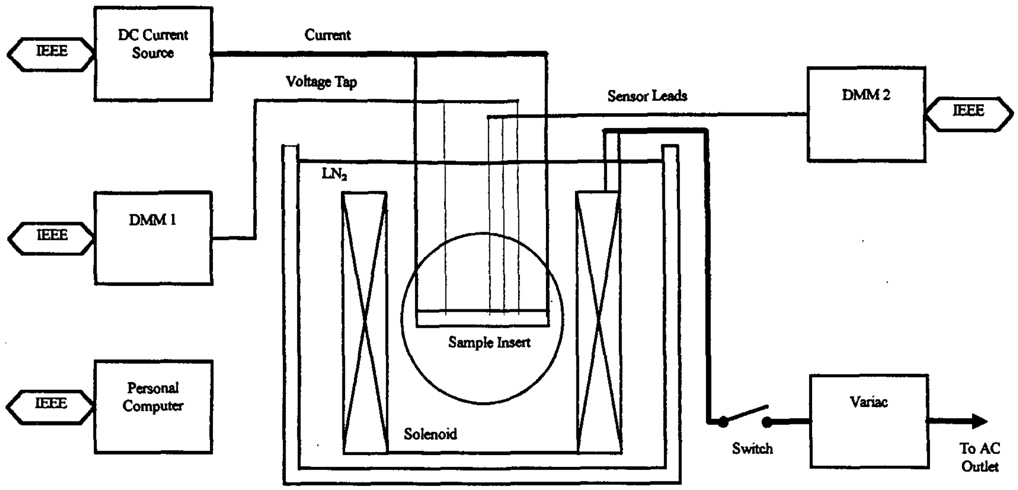

Fig. 1. Block diagram for measurement of magnetic losses of HTSC. Details of the sample insert are shown in Fig. 2.

reading of the temperature rise, ΔT, is taken. The power loss of the heater is equal to

$$Q = I^2 R_h, \tag{2}$$

where Q is the loss, I is the current and R_h is the heater resistance. The calibration curve is given in Fig. 3.

The AC loss measurement was conducted by switching on the variac for period τ_m and recording the temperature rise ΔT. This is repeated for different magnitudes of applied field. Using (1) the total loss can be calculated.

The sample is a 6 centimeter long (Bi,Pb)SrCaCuO-2223 tape prepared by powder-in-tube techniques. It has a transition temperature of about 104K as can be seen in the R-T characteristic in Fig. 4, that is also obtained using the instrumentation rig. The measurements are performed at the frequency of 50 Hz. Table 1 overviews the sample configuration for these measurements.

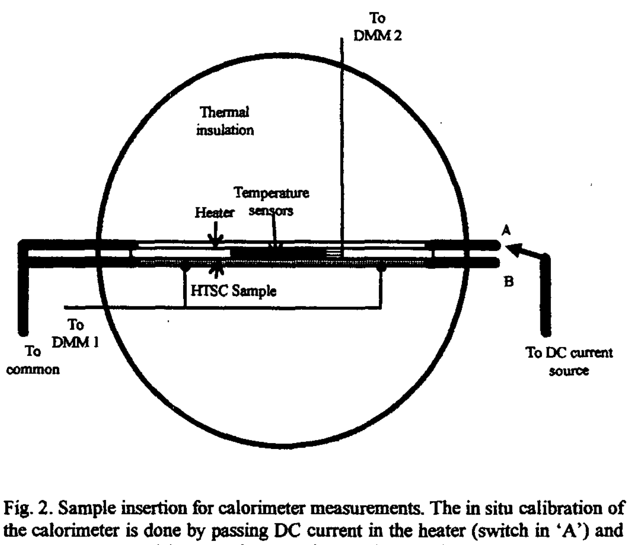

Fig. 2. Sample insertion for calorimeter measurements. The in situ calibration of the calorimeter is done by passing DC current in the heater (switch in 'A') and the measurement of the critical current is done by switching the current source in 'B'.

TABLE I
SAMPLE CONFIGURATION

Sample	Number of filaments	Thickness (mm)	Width (mm)	DC critical current (A)
MF-37	37	0.26	3.62	24

III. Results and Discussion

This section gives an overview of the theoretical calculation and results obtained from the calorimetric measurement of the losses of the sample subjected to a longitudinal and perpendicular alternating field.

A. Theoretical Approximation

By assuming that the whole sample is silver, the eddy

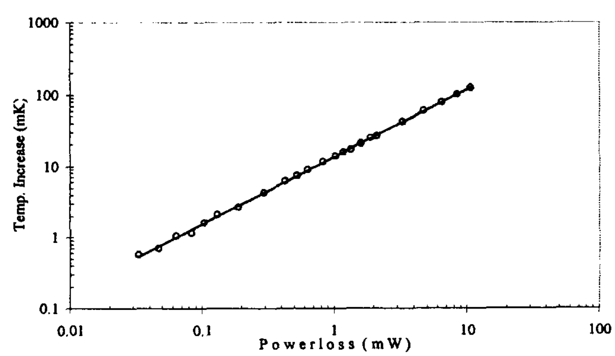

Fig. 3. Calibration curve of the calorimeter. The thermal resistance of the calorimeter was determined using this curve.

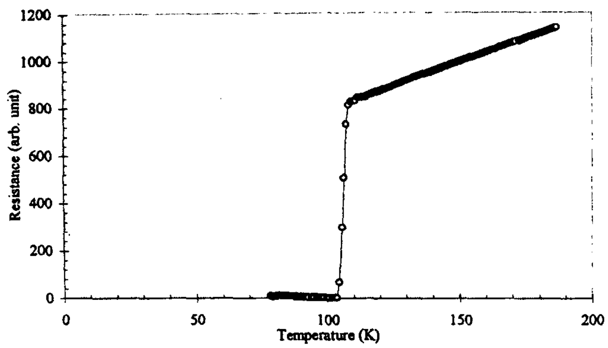

Fig. 4. Temperature dependence of the sample resistance.

current loss can be calculated using

$$P_e = \frac{8\pi^2 f^2 B_m^2 a^3 d}{3\rho} \text{(W/m)}, \tag{3}$$

where f is the AC frequency, B_m is the peak value of applied field, a and d are the half width and thickness of the wires respectively and ρ is the resistivity of the silver at 77K. In fact the eddy current losses are also generated by the heater, which is made of silver strip with the same dimension of the sample. Therefore (3) is reasonably correct.

The hysteresis losses of the sample are approximated using the following equation

$$P_h = \frac{8adB_m^3 f}{3\mu_0 B_p} \text{(W/m)}, \tag{4}$$

for $B_m < B_p$, and

$$P_h = \frac{8adB_m B_p f}{\mu_0}\left(1 - \frac{2B_p}{3B_m}\right) \text{(W/m)} \tag{5}$$

for $B_m \geq B_p$,

where B_p is the full penetration of parallel field and is equal to $\mu_0 J_c a$ (T) and J_c is the critical current density of the sample.

However, the hysteresis loss of a superconducting wire is calculated with

$$P_h' = \alpha P_h \text{(W/m)}, \tag{6}$$

where α is the a factor of value 2/3 as directed by Ishii et al. by assuming that the cross-section of the superconducting cores is an ellipse and that the magnetic flux penetrates parallel to the longer axis of the core.

B. Measurement Results

Fig. 5 shows the results of the AC loss measurement for the 37-multifilamentary sample exposed to a longitudinal alternating field. The thin solid line indicates the eddy current component of the silver part calculated using (3) and the thick solid line represents the approximation of the hysteresis loss using (6). At this frequency it is evident that the hysteresis loss is significant because its value is nearly two orders higher than the eddy current component. For the region below 30 mT the value of the hysteresis loss is lower than the estimation and it is higher beyond that point. The existing coupling loss between the filaments that is significant at relatively high magnetic field can cause this.

When the sample is subjected to a perpendicular field the loss becomes more than one order higher for the same magnitude of the field as can be seen in Fig. 6. This is due to the anisotropic behavior of the grains in the sample. The field applied perpendicular to the grain causes local current and hence the total losses become high.

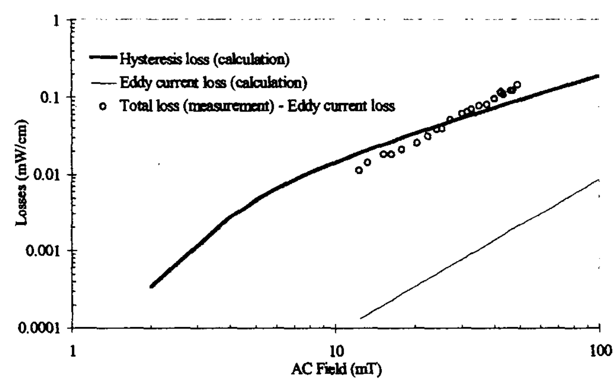

Fig. 5. AC losses of a 37-multifilamentary wire exposed to a longitudinal AC field. The hysteresis losses of the sample are of the same order as the calculation results.

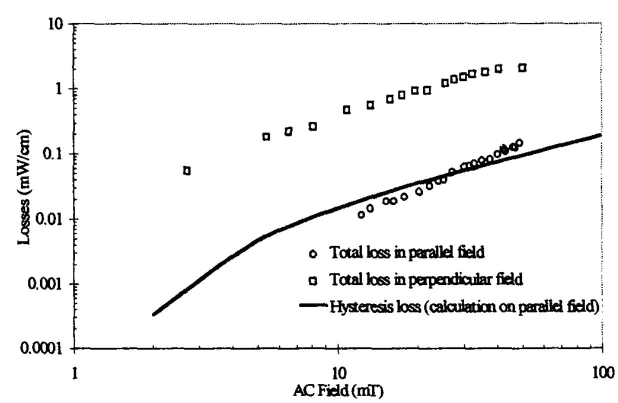

Fig. 6. Perpendicular and longitudinal magnetic loss in a 37-multifilamentary HTSC tape.

IV. Conclusions

The developed calorimeter and the experimental rig have been used to measure the total losses of the sample with the accuracy of microwatts per centimeter. In this work the AC losses of the HTSC tapes exposed to an alternating field parallel to the length of sample have been investigated using those methods. The total losses consist of the hysteresis part of the superconducting cores and the eddy current of the silver sheath.

The hysteresis part of the sample is achieved by subtracting the eddy current loss from the total loss. The measurement results correspond to the theoretical estimation using the critical state model. However, the coupling between the filament in the multifilamentary wires contributes additional losses at relatively high external magnetic field.

Due to the anisotropic habits of the grains in the superconducting part, the magnetic losses become one order higher. This is apparent when measuring the losses of the sample that is exposed perpendicularly to the field.

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